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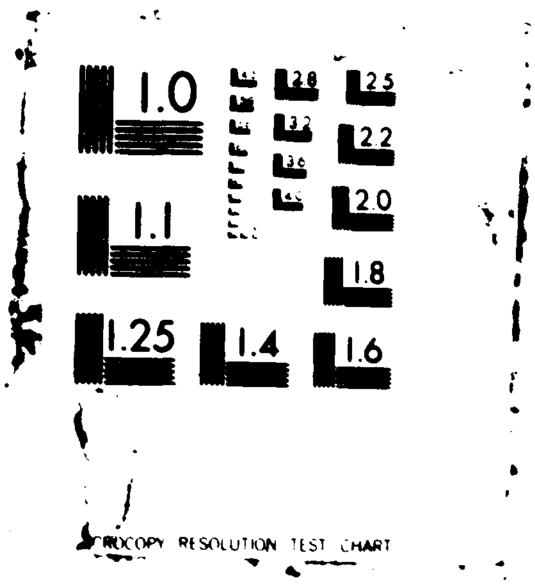
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J. VLA OBSERVATIONS OF A SOLAR NOISE STORM

KENNETH R. LANG AND ROBERT F. WILLSON

Department of Physics and Astronomy

Tufts University

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ABSTRACT

We present the first Very Large Array (VLA) observations of the Sun at 92 cm wavelength (328 MHz). A solar noise storm, which lasted at least 3 hours, was detected at this wavelength; it consisted of burst-like spikes superimposed on a slowly varying background, and both storm components were 95 $\pm$ 5% right-hand circularly polarized. A long-duration soft X-ray event preceded the radio radiation by 30 m, suggesting a disturbance moving outwards at a velocity of $v = 78$ km s^{-1}. The 92-cm noise storm was resolved with an angular resolution of 9" for time intervals as short as 13 s. During the onset and early phases, the storm consisted of four compact sources, each with an angular diameter of 40", oriented within an elongated source with angular dimensions of 40" x 200". During the subsequent hour the most intense emission was located in two 40" sources separated by 100". Snapshot maps revealed a persistent elongated source at successive peaks, with a scatter in the source position. A systematic position shift of $\Delta\theta_I > 15"$ can be produced by the Earth's ionosphere, but these effects can be removed by frequent observations of a nearby calibrator source. Our observations confirm previously reported trends for a decrease in source size at higher frequencies, but they suggest a hitherto unresolved complexity in source structure. The new VLA results are also consistent with previous observaitons of noise storm polarization and height. The VLA can potentially resolve both the burst and continuum components of noise storms, while also detecting the effects of anisotropic scattering in the corona. The high angular resolution and large collecting area of the VLA may either lead to the detection of the second harmonic of the storm plasma frequency or establish important limits to it.

I. INTRODUCTION

Noise storms are the most common phenomenon observed on the Sun at decimetric and metric wavelengths (see Elgaroy 1977 and Kai, Melrose and Suzuki 1985 for reviews). Here we will present a brief synopsis of their properties, thereby providing a perspective for our subsequent observations and discussion.

The noise storms consist of a slowly-varying, wide-band continuum radiation with superimposed short-lived, narrow-band bursts. The background continuum, which is usually observed between 50 and 350 MHz, normally continues for a few hours and sometimes lasts for days. The noise storms are clearly associated with solar active regions, but there is no clear-cut association with solar flares.

Literally thousands of storm bursts are emitted, each with a bandwidth between 2 and 10 MHz and a duration of 0.1 to 2s. These bursts have been designated Type I bursts in order to distinguish them from other types of solar bursts. They are superimposed upon a continuum that is not thought to be composed of numerous bursts.

Both the background continuum and the bursts are strongly circularly polarized (up to 100%), usually with the same sense and degree of polarization. This polarization is attributed to coronal magnetic fields that connect with underlying sunspots. The sense of circular polarization usually corresponds to the ordinary mode of wave propagation in the magnetic field of the nearest leading spot; right-handed circular polarization therefore corresponds to negative magnetic polarity with the magnetic field lines pointed in towards the Sun.

It is thought that noise storms are some kind of plasma radiation emitted at the plasma frequency, and this is consistent with circular polarization in the ordinary mode. The emission originates in the lower solar corona at altitudes of between 0.1 and 0.5$R_\odot$ (solar radii) above the photosphere. Radiation at lower frequencies originates at higher altitudes where the electron density and plasma frequency are smaller than those at lower altitudes. The inferred electron density at a given altitude is greater than that of the quiet corona at this altitude, suggesting an origin in closed magnetic loops (coronal loops) that contain a high-density plasma.

II. OBSERVATIONS

a) Time Profile

The VLA was used to observe the solar active region AR 4732 in the A configuration between 1300 UT and 2400 UT on 29 May 1986. The position of AR 4731 was on 0N 40W on this day. The array was divided into two subarrays with 12 antennas operating at 92 cm wavelength (328 MHz) with a 3.12 MHz bandwidth and 15 antennas operating at 21 cm wavelength (1420 MHz) with a 12.5 MHz bandwidth. The beamwidth of the individual antennae at 21 cm was 31.5' and included the active region AR 4731 located at 6S 50W at 1300 UT on 29 May. The individual antennae had beamwidths of 138' at 92 cm, which includes the entire visible disk of the Sun, but AR 4731 and AR 4732 were the only active regions on the visible solar surface during our observations.

All four Stokes parameters were sampled every 6.67s, and the data were calibrated by observing 3C 84 every 30 minutes. The flux density of 3C 84 was assumed to be 32.0 Jy and 8.0 Jy at 21 cm and 92 cm, respectively.

As illustrated in Figure 1, a noise storm was detected at 92 cm between about 1930 UT and 2400 UT. No noise storm was detected at 21 cm, but this is not surprising for plasma radiation at this wavelength would be absorbed in the overlying solar atmosphere. The 92 cm noise storm consisted of numerous burst-like spikes superimposed on slowly-varying emission.

The burst-like spikes are analogous to Type I bursts, but the observed data have relatively long integration times that probably integrate the emission of several Type I bursts or chains of bursts. The slowly-varying emission resembles the background continuum of a typical noise storm. Both the burst-like spikes and the slowly-varying background emission were 95 ± 5% right-hand circularly polarized.

A long-duration soft X-ray event (also shown in Figure 1) may provide a clue to the triggering mechanism for the 92-cm noise storm that followed it by about 30 m. The noise storm may have been triggered by a disturbance moving outwards from the source of the X-ray radiation. If the sources of radiation in the two spectral regions are separated by a distance of 0.2 R_{O}, then the disturbance moves at a velocity of v = 78 km s^{-1}.

b) Observations with High Angular Resolution

The VLA can provide angular resolutions that are more than an order of magnitude better than those of previous observations of solar noise storms. It is capable of 5" angular resolution at 92 cm wavelength (328 MHz). By way of comparison, the Culgoora and Nancay Radioheliographs had respective beamwidths of ~2.0' and ~1.3' at 160 MHz.

As illustrated in Figure 2, the onset and first maximum of the 92 cm noise storm consisted of four compact sources, each about 40" in angular diameter, that were arranged within an elongated 40" x 200" source. During the subsequent hour, the 92 cm emission was concentrated within the same elongated source, but it was most intense in two 40" sources separated by 100". For comparison, the tapered beamwidth of 9" x 9" is shown as a small black dot.

The VLA also has the capability of making snapshot maps at time intervals as short as 3 s. As an example, Figure 3 shows VLA snapshot maps of successive peaks in the emission of the 92 cm noise storm shown in Figure 1 (peaks 3, 4, 5, 6 and 7). These peaks originate in an elongated source that has a persistent, unchanging shape with half-power angular dimensions of about 40" x 120". The scatter in the locations of the most intensive emission is real, but there were no apparent trends in the location change.

Refraction in the Earth's ionosphere will produce a systematic shift in source position. This shift is smallest at source transit and largest near the horizon. It is also relatively large at sunrise and at times of increased solar activity.

When theoretical formulae given by Komesaroff (1960) are combined with measurements of the ionosphere's electron density, Stewart and McLean (1982) obtain a noontime ionospheric shift of $\Delta\theta_I = 60''$ at 160 MHz. Because refraction scales as the inverse square of the observing frequency, we would expect $\Delta\theta_I = 15''$ at 92 cm (328 MHz). This is consistent with the observations of Erickson (1984) at 80 MHz and with

those of Spoelstra (1983) at 600 MHz. The systematic position shift, $\Delta\theta_I$, can be automatically removed from future VLA data by frequent observations of a nearby calibrator source, but a smaller, random shift should remain because of the fluctuating component of the ionosphere's electron density.

III. DISCUSSION

c) Comparisons with Previous Results

Observations of noise storms with the Culgoora radioheliograph at two frequencies (80 and 160 MHz) and with the Clark Lake facility at several frequencies between 20 and 65 MHz suggest that the higher frequency radiation originates in more compact sources (Gergely and Kundu 1975; Stewart 1976; McLean 1981). This downward trend in source size with increasing frequency was also suggested by a small sample of storm sources observed with the Culgoora instrument at 80, 160 and 327 MHz (Sheridan, et al. 1983). Characteristic half-power angular sizes of $\theta \sim$ 6', 3' and 1.5' were respectively obtained at 80, 160 and 327 MHz.

However, storm sources are also often unresolved with even the largest radio telescopes, and the telescope beamwidths exhibit a disturbingly similar downward trend with increasing frequency. There have been no systematic high-resolution investigations of the size and shape of solar noise storms because of the poor resolving power of the existing radio telescopes.

Although the new VLA observations are not inconsistent with previous observations of a decrease in source size at higher frequencies, they do suggest that complex source structure will be revealed at high resolution. Such complexity may well rule out a

simple model in which noise storms originate within a conical column (diverging magnetic fields) whose size increases with height (McLean 1973, 1981).

The new VLA results are also consistent with previous polarization observations. The sense of circular polarization should correspond with that of the ordinary mode expected from plasma radiation in a strong magnetic field (Dulk and Nelson 1973; Stewart 1985). Right-handed circular polarization is therefore associated with negative magnetic polarity in which the magnetic field is directed away from the observer and into the Sun. Left-handed circular polarization is similarly associated with positive magnetic polarity in which the magnetic field is directed towards the observer.

Because our observed storm was 95 ± 5% right-hand circularly polarized, it should originate in coronal magnetic fields that are connected with the dark, negative-polarity magnetogram features shown in Figure 4. Because the noise storm projects radially downward to the more central active region (AR 4732), the storm source is most likely associated with magnetic fields that connect to the dark dominant, leading spot of AR 4732. As a matter of fact, noise storms are usually related to the dominant, leading sunspot of the associated active region.

Thus, the storm source is most likely plasma radiation in magnetic fields connected to the dark, leading spot of AR 4372. As illustrated in Figure 4, the angular size and distance of the noise storm are nevertheless larger than the angular separation of the leading and

trailing spots of AR 4372. If the storm originates in closed magnetic loops, then they may not be solely connected to the bipolar AR 4372. Large-scale magnetic fields may instead connect the leading spots of the two active regions AR 4371 and AR 4372. A similar model has been proposed by Kai and Sheridan (1974) for other noise storms. However, our observations cannot by themselves rule out the possibility of open magnetic field lines that extend out into the interplanetary medium.

The height of a noise storm can be found if we assume that it lies radially above the associated sunspot. Under this assumption, the average observed heights, h, at 160 MHz and 80 MHz were h = 0.4 $R_\odot$ and h = 0.8 $R_\odot$ above the photosphere (Stewart 1976). Noise storms at the higher frequencies of 327 MHz and 408 MHz have estimated heights of h = 0.2 $R_\odot$ and h = 0.1 $R_\odot$, respectively (Sheridan, et al. 1983; Clavelier 1967).

Thus, the average height of the noise storm source decreases with increasing frequency. Our observations also support this conclusion. The angular displacement of the noise storm from its associated spot is $\Delta\theta$ = 2.3' (when corrected for ionospheric refraction), and this displacement corresponds to a radial height of h = $1.0 \pm 0.2 \times 10^{10}$ cm = 0.15 ± 0.03 R_o.

At our observing frequency of ν = 328 MHz, we infer an electron density of $N_e = 1.4 \times 10^9$ cm^{-3} for the height h = 1.0×10^{10} cm from the condition that $\nu = \nu_p$, where the plasma frequency $\nu_p = 8.9 \times 10^3 N_e^{1/2}$ Hz. The plasma radiation will dominate over thermal cyclotron radiation

when $\nu = \nu_p >> \nu_H$, where the gyrofrequency $\nu_H = 2.8 \times 10^6 H$ Hz and H is the magnetic field strength in Gauss. Thus, we have H << 100 G in the storm source at a height of $h = 1.0 \times 10^{10}$ cm above the photosphere. The condition for suppression of the extraordinary mode of wave propagation, with the resultant escape of the ordinary mode, similarly requires H << 100 G at this height.

d) Future VLA Potential

The VLA can potentially resolve noise storm sources with an angular resolution of 5" at 92 cm wavelength. Snapshot synthesis maps can be made with this resolution for intervals as short as 3 s, which is comparable to the duration of chains of Type I bursts. The observing bandwidth, $\Delta\nu$, can be comparable to that of Type I bursts ($\Delta\nu \sim 6$ MHz), and an improvement in VLA integration time to 0.1 s would permit observations of individual Type I bursts.

As illustrated in Section II, the VLA has already been used to resolve noise storm sources with an angular diameter of 40". This diameter corresponds to a linear size, L, of $L = 3 \times 10^9$ cm at the Sun's distance. Waves moving at the velocity of light would cross this dimension in a time, $\tau = 0.1$ s. Because nothing can move faster than the velocity of light, the duration, τ, of a source with this dimension must be $\tau > 0.1$ s. The observed limit to the duration of individual Type I bursts is also $\tau > 0.1$ s (Elgaroy 1977). The VLA resolution of 5" therefore seems to be fully capable of resolving the Type I burst emitters.

The VLA can probably distinguish between the two principal components of noise storms, thereby resolving the sources of Type I bursts and the background continuum for the first time. Future VLA observations will therefore probably determine if the two sources have comparable or different sizes, and if one of them resides within the other.

The VLA can also potentially detect the effects of scattering on field aligned density inhomogenieties. This anistropic scattering was first proposed to reconcile the narrow bandwidths and apparently-large sizes of some Type I bursts at 169 MHz (Bougeret and Steinberg 1977). As illustrated in Section II, the 92 cm (328 MHz) VLA observations have resolved elongated sources that were predicted by the scattering theory.

Both the fundamental and the second harmonic of the plasma frequency might be detected if an intense noise storm is observed with both the VLA and a smaller patrol-type solar radio telescope. The fundamental plasma radiation is all that has been previously observed, primarily because of the low brightness temperature of the harmonic. The large collecting area and high angular resolution of the VLA will vastly improve detection thresholds. For instance, observations at twice the frequency of strong Type I bursts indicate that the flux of the associated second harmonic emission is less than 0.001 of the fundamental (Jaeggi and Benz 1982). Future VLA observations should improve this limit by more than an order of magnitude, or else detect the second harmonic, thereby providing important constraints to theoretical explanations of noise storms (see Benz and Wentzel 1981).

e) Acknowledgements

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FIGURE LEGENDS

Fig. 1. The time profile of a solar noise storm observed with one interferometer pair of the Very Large Array (VLA) at 92 cm wavelength (top) is compared with the soft X-ray emission detected by the GOES satellite (bottom). The separation of the two antennae was 0.8 km, providing an angular resolution of 240" at 92 cm during source transit. Here the data have been smoothed over 33.3 s. Spike-like bursts are superimposed upon a slowly-varying background; both of these components were 95 ± 5% right-hand circularly polarized. VLA maps covering the intervals denoted by 1 and 2 are shown in Figure 2, and VLA snapshot maps of the spikes denoted by 3, 4, 5, 6 and 7 are presented in Figure 3. The X-ray emission precedes the 92 cm radiation by about 30 m. If we assume that the noise storm is excited by a disturbance that originates during the soft X-ray event at a distance of 0.2 $R_\odot$, then that disturbance must travel outwards at a velocity of $v \sim 78$ km s^{-1}.

Fig. 2. Very Large Array (VLA) synthesis maps for a one hour interval that includes the beginning of a solar noise storm (left) and for the subsequent one hour interval (right). These two intervals are respectively denoted by 1 and 2 in Figure 1. Both the onset and early excitation of the 92 cm noise storm consist of four sources with angular diameters of 40" and a total angular extent of 200". Emission in the two central 40" sources became more intense later in the noise storm (see Figure 3). The fiducial marks on the axes are separated by 100", and the contours mark levels of equal brightness temperature T_B, with an outermost contour of $T_B = 1.0 \times 10^6$ K and a contour interval of 7.2 x 10^5 K. The synthesized beamwidth is denoted by the black spot.

Fig. 3. Very Large Array snapshot maps of successive peaks in a solar noise storm at 92 cm wavelength. These peaks are denoted by 3, 4, 5, 6 and 7 in Figure 1. The snapshot maps, each lasting 13 s or 30 s, show no substantial change in the shape or size of the storm source over a period of two hours. Here the synthesized beamwidth is denoted by the black dot, and the fiducial marks on the axes are separated by 100". The contours mark levels of equal brightness temperature, T_B, with an outermost contour of $T_B = 3.8 \times 10^6$ K, a contour interval of 2.5×10^6 K and a peak brightness temperature of $T_B = 1.6 \times 10^7$ K.

Fig. 4. A Very Large Array (VLA) synthesis map of a solar noise storm at 92 cm wavelength is superimposed on a Kitt Peak National Observatory (KPNO) magnetogram taken on the same day. The VLA map covered the one hour time interval between 2300 and 2400 UT; its synthesized beamwidth is denoted by the black spot. The contours mark levels of equal brightness temperature, T_B, with an outermost contour of $T_B = 1.0 \times 10^6$ K and a contour interval of 7.2×10^5 K. Dark areas on the magnetogram correspond to negative magnetic polarity with the magnetic field lines pointing in towards the Sun; whereas light magnetogram areas correspond to outward regions of positive magnetic polarity. Two dipolar regions are shown on the magnetogram - AR 4731 near the limb and AR 4732. The 92 cm source is attributed to plasma radiation in the ordinary mode of wave propagation along magnetic field lines connected to the dark negative spot of AR 4732. The angular displacement between this spot and the 92 cm source corresponds to a radial altitude of about $0.2R_\odot$ above the photosphere. The magnetogram was kindly provided by Jack Harvey of the National Solar Observatory.

KENNETH R. LANG and ROBERT F. WILLSON

Department of Physics and Astronomy

Robinson Hall

Tufts University

Medford, MA 02155

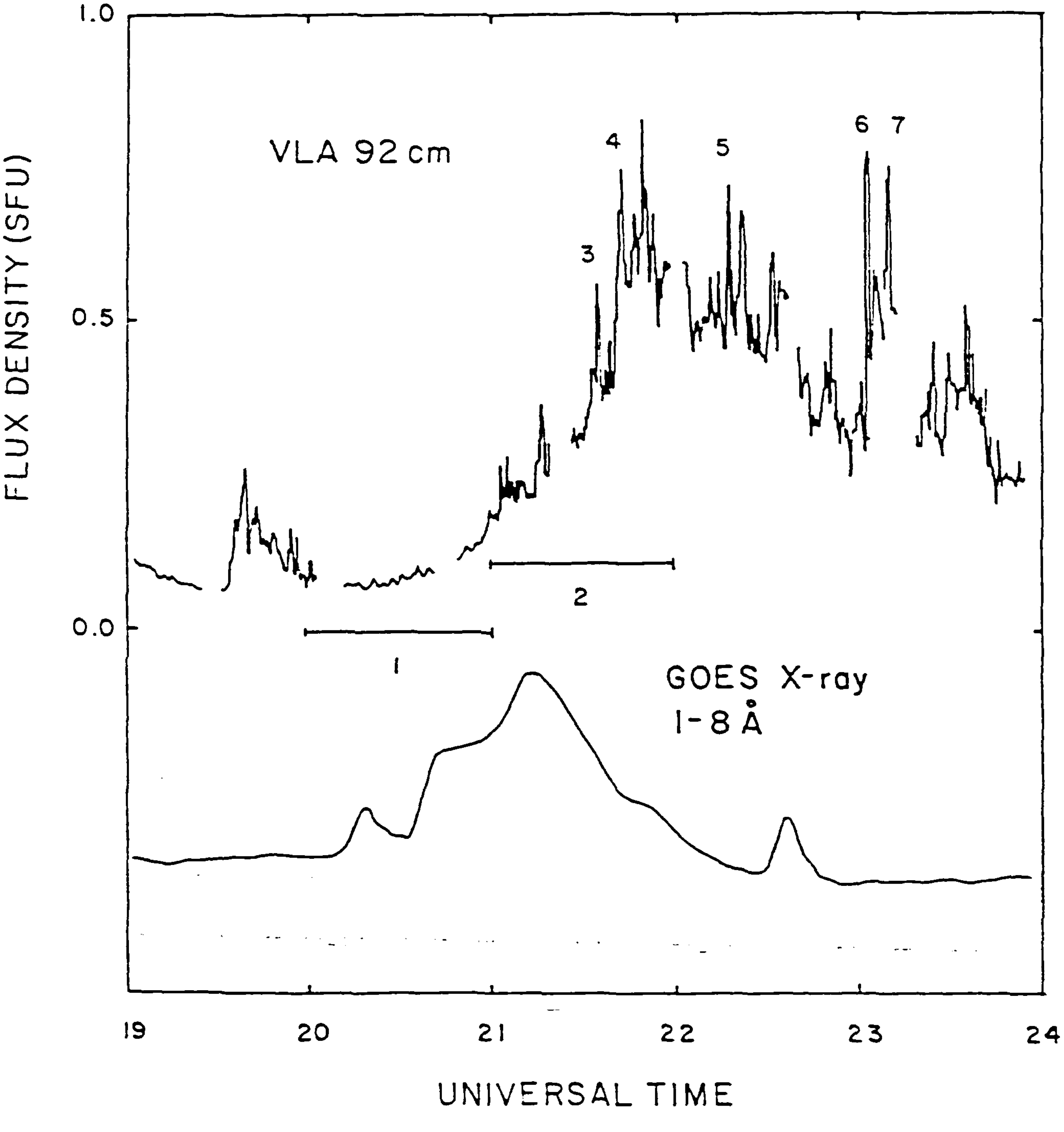
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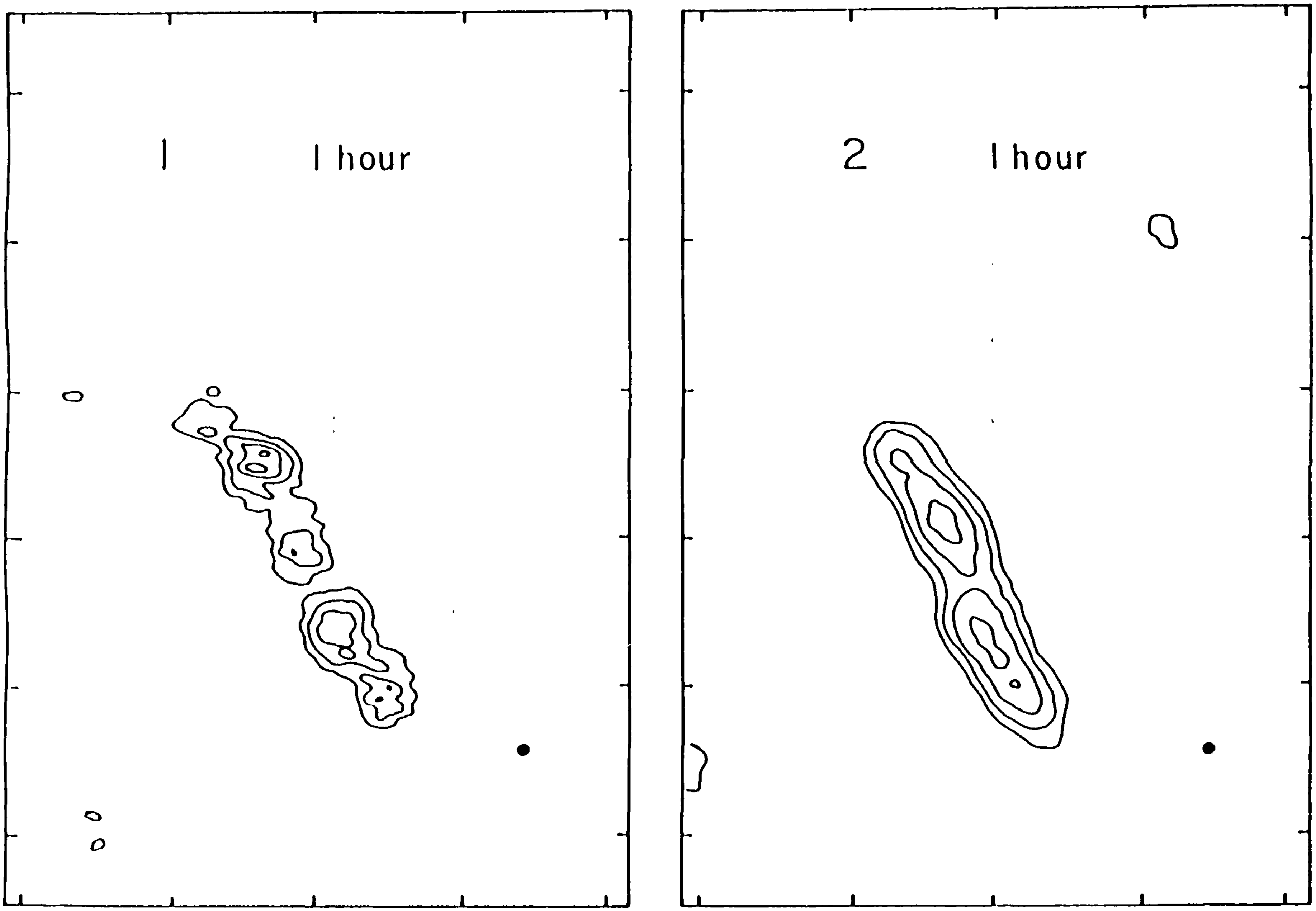
Fig. 1



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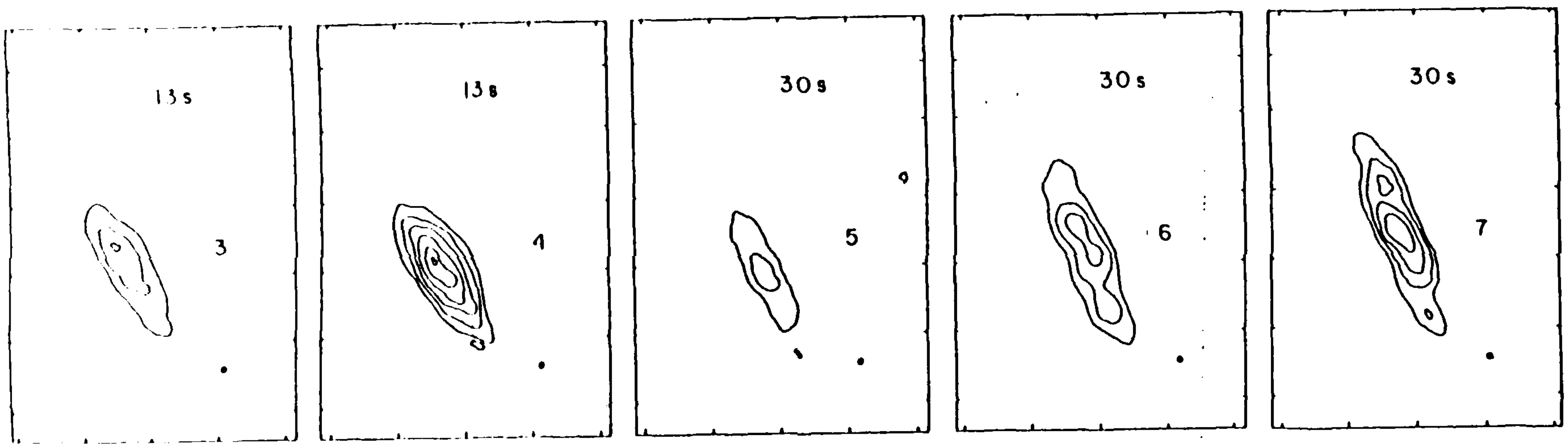
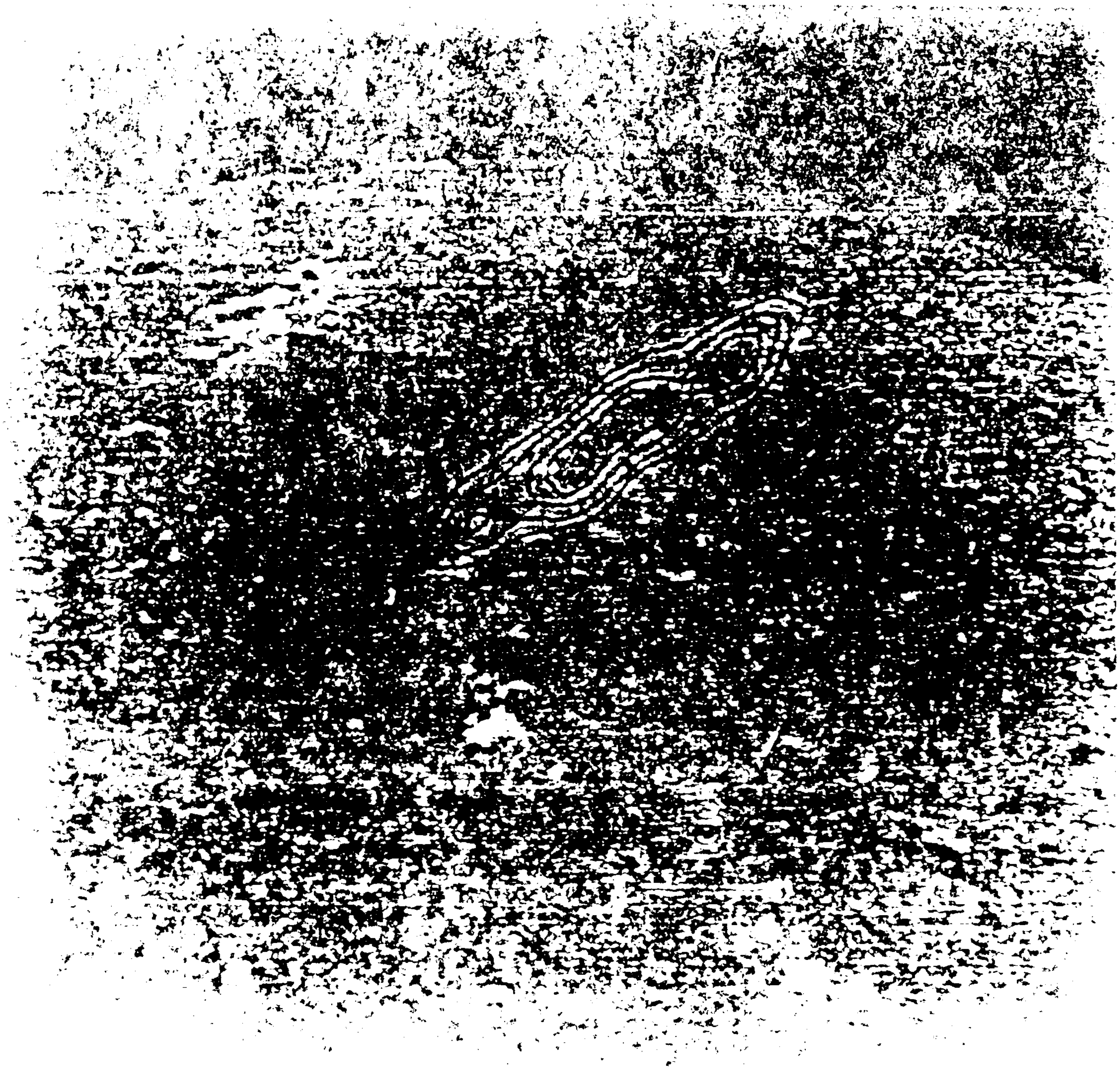


Fig. 3.



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